BOTTOM CURRENT MEASUREMENTS IN THE HEAD OF MONTEREY SUBMARINE CANYON

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Submitted in partial fulfillment of
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MASTER OF SCIENCE

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ABSTRACT

Bottom current measurements were taken in the head of Monterey Submarine Canyon in a water depth of 130 meters (72 fathoms) utilizing an Ekman current meter placed 480 centimeters (15.7 feet) above the bottom. Currents were observed to follow the canyon axes, and flow was seaward (down-canyon) on the rising tide and coastward (up-canyon) on the falling tide. Current speed was sometimes fairly steady and other times variable. It ranged between 0 and 41 centimeters per second (0 to 0.8 knot) and had a median speed of 10 cm/sec (0.2 knot). The six hours centered around low tide generally had considerably stronger currents than the similar period of time centered around high tide.

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I. INTRODUCTION

The purpose of this paper is to present the results of bottom current measurements obtained in the head of the Monterey Submarine Canyon in a depth of approximately 130 meters. The currents were measured at a height above the bottom of 4.8 meters using an Ekman current meter. A total of 77 current readings were made under various conditions of tide and wind. These and other environmental factors were examined with regard to their possible influence on the bottom currents. The measurement system is also described.

In the course of this study, a literature survey was made of current observations in submarine canyons by other investigators. An abstract of the references that were found is presented in Appendix I. The following conclusions were drawn from this survey:

1. Relatively few bottom current studies or observations have been made in submarine canyons. Measurements on a continuous time basis are especially lacking.[1]

2. Canyon currents are common and occur at many depths. In

[1] Deepstar Log #1 reported that in November 1964 a Savonious Rotor current meter and continuous recorder were placed four feet above the bottom on the slope north of Scripps Canyon in a water depth of 50 meters.

general, they tend to follow the canyon axis both up and down-canyon.

3. Magnitudes up to 26 cm/sec (0.5 knot) have been reported. The currents may be oscillating, pulsating, or steady.

4. Little is definitely known about the causes of bottom currents. Apparently only one systematic study, that by Shepard, Revelle, and Dietz (1939), has been made to determine the possible causes of the currents. These investagators suggested that the currents were related to "internal waves or irregularly moving eddies with vertical axes". Possible causes proposed by other investigators include tidal influence, surf beat, and seaward return flow of water carried inshore by surface waves (Shepard, et al.,1964; Stetson, 1937; Appendix I).

In light of these conclusions, the present study was designed with the purpose of obtaining a time series of current observations that could be subjected to systematic analysis for possible causitive factors.

Current measurements were obtained in the canyon axis at a location approximately one mile west of Moss Landing situated at the head of Monterey Bay. Figure 1 shows the geographical relationship between Monterey Canyon and Monterey Bay, and Figures 2 and 3 display the bathymetry of the canyon head and

the metering station. Moss Landing is further shown in an aerial photograph in Figure 4.

Three factors controlled the selection of the station location:

1. The station had to be in the canyon axis.

2. It had to be readily and reliably located for repeat observations. This was easily accomplished by the use of range lines; numerous objects were visible on shore for this purpose.

3. It had to meet a maximum depth limitation. This was imposed by the length of cable that was aboard the research boat for the type of measurement system that was used.

Because of the latter limitation, the current station was located very close to the junction where two tributary branches from the main channel. For purposes of interpretation of the data, a station located in the main channel a short distance down-canyon in a slightly greater depth would have been more desirable. Shoaler depths were avoided because of the complexity of the bottom topography.

The basic concept of current measurement was to take repeated observations of approximately ten-minute duration over a period of several hours so as to cover a significant part of a tide stage on a given day. It was anticipated that variations in

the current having a tidal period might be found. The duration of a survey on a given day was limited by availability of the boat and boat crew.

Measurements were obtained on nine different days during February and March 1965. The first two days were used mainly to check out the current measurement system and to establish a suitable station. The other seven days produced a series of readings covering an average daily duration of five hours, with the frequency of readings being approximately two per hour.

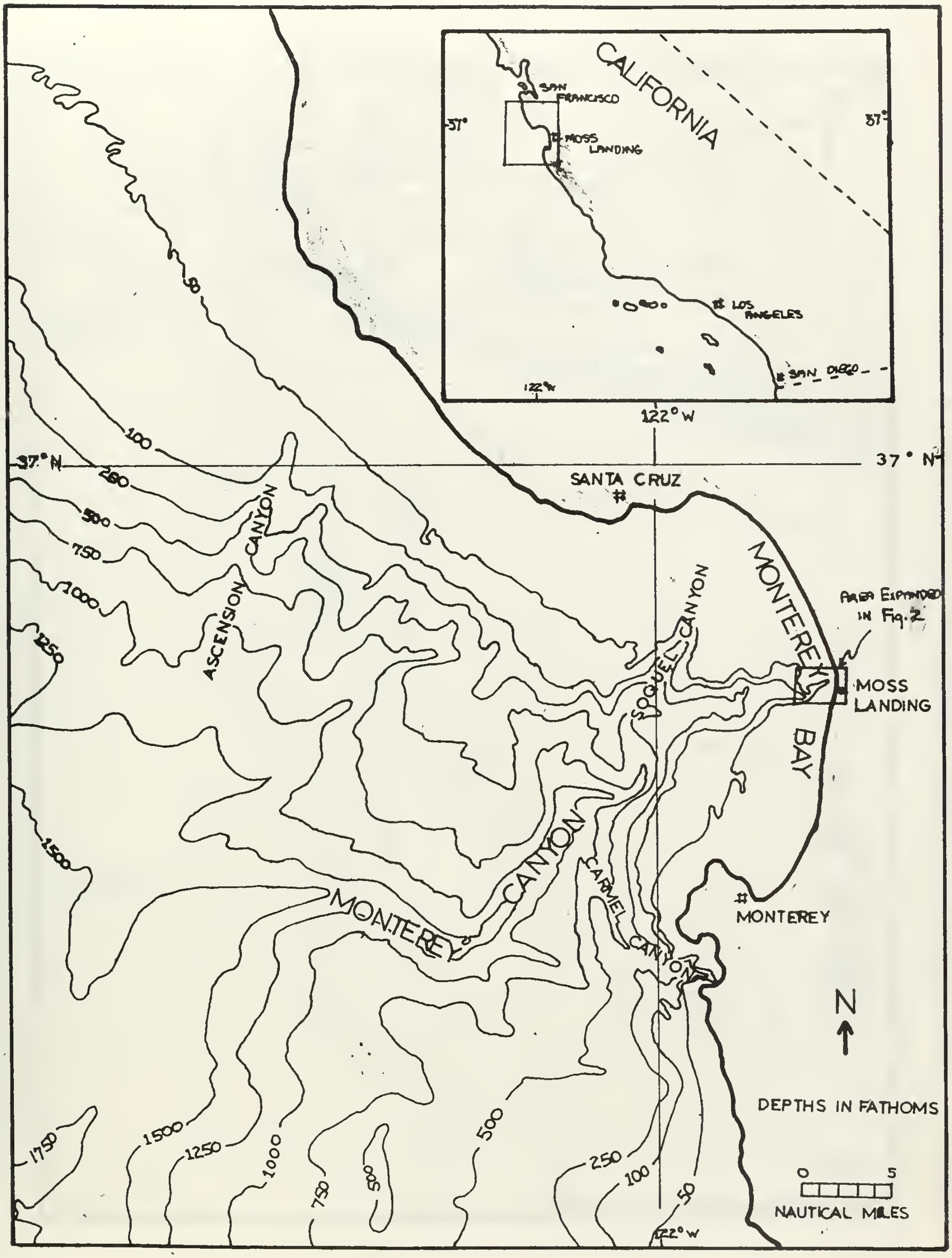

Figure 1. Relationship of Monterey Canyon to Monterey Bay (adapted from Shepard and Emery, 1941).

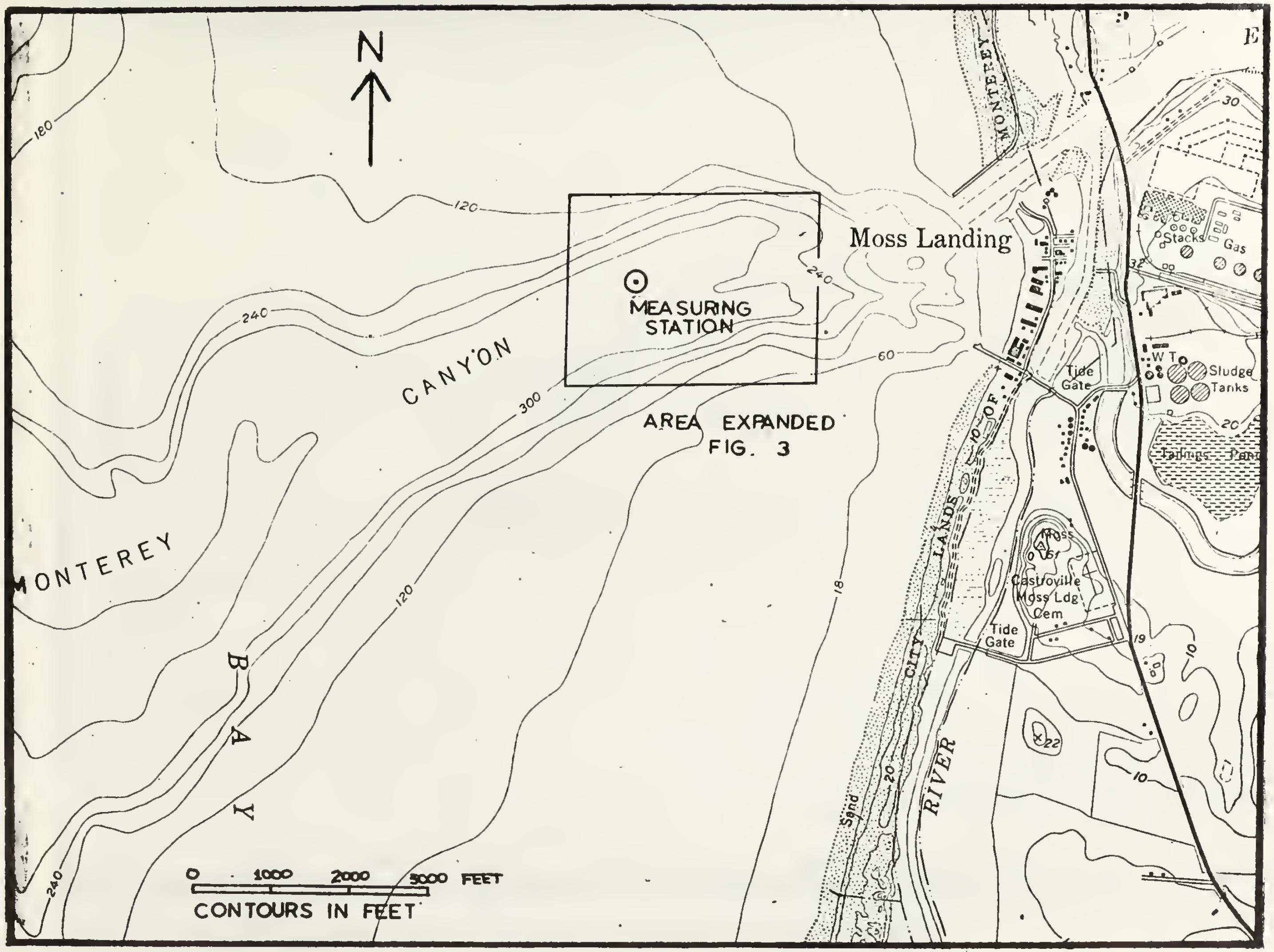

Figure 2. Hydrography in the Head of Monterey Canyon (from U.S.G.S. Moss Landing Quadrangle).

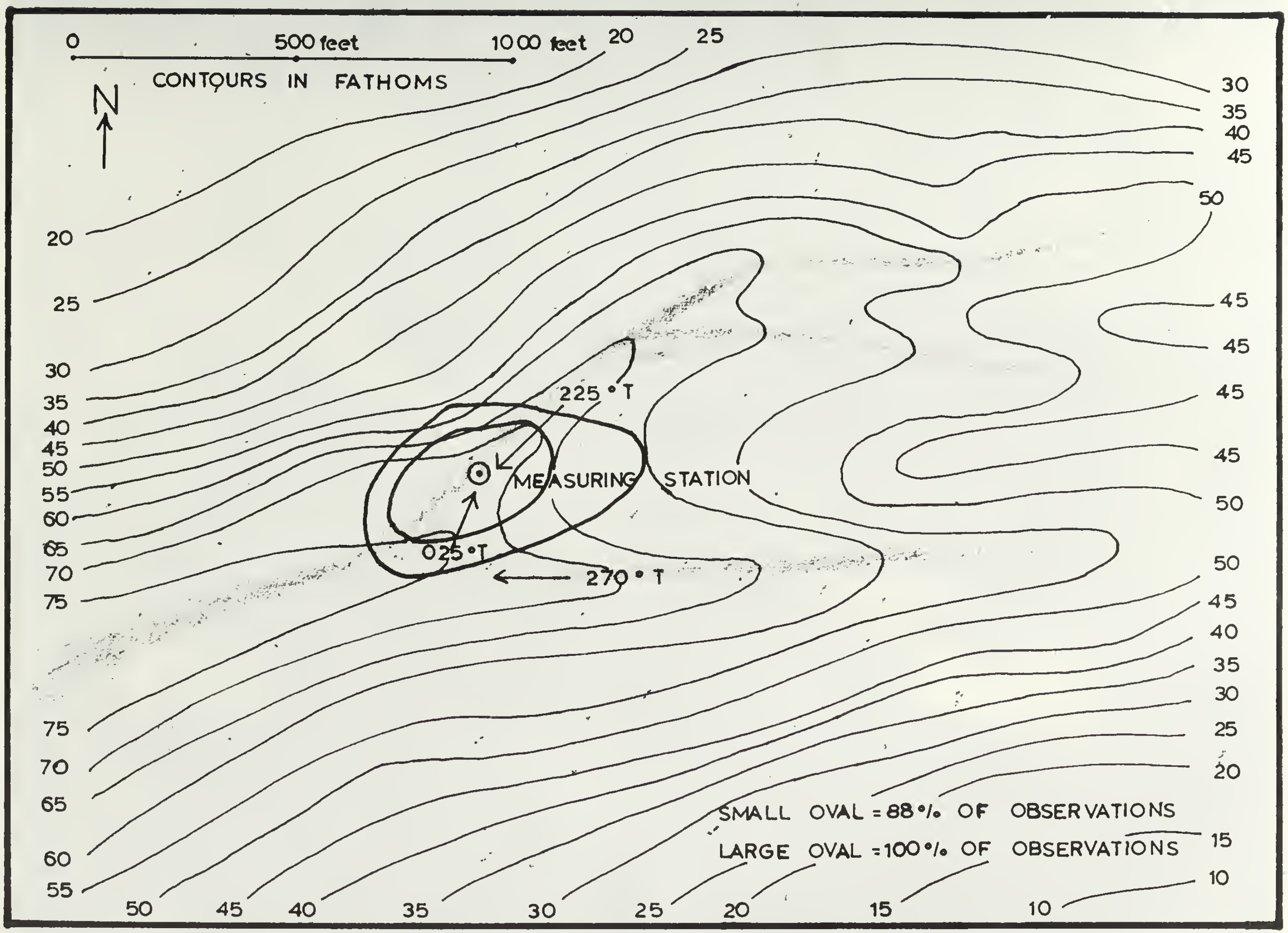

Figure 3. Hydrography in the Vicinity of the Measuring Station.

Figure 4. Aerial Photograph of Moss Landing, California (reproduced by permission of A. E. Grensted Photography). The X marks the approximate position of the measuring station.

II. TOPOGRAPHY IN THE VICINITY OF THE MEASURING STATION

Figure 3 shows the detailed bathymetry around the metering site based on soundings from U. S. Coast and Geodetic Survey Hydrographic Survey 5406. This was supplemented by fathometer indicator readings made during the study. The contours are based on a sounding density of approximately one sounding per 250 square meters. Small-scale detail was beyond the equipment capability of this investigation and is lacking.

It may be noted that seaward of the measuring station the canyon is a single, well-defined channel, but that in a depth of about 75 fathoms it divides into a north and south branch. The branches, in turn, divide into smaller tributaries in very shallow water.

The topography between the north and south branches is comparatively gentle in the immediate vicinity of the measuring station. The slope of both branches averages approximately ten degrees in the first 100 meters up-canyon from the measuring station. For 100 meters down-canyon, the canyon axis appears to have a slope of only about three degrees.

The fathometer readings revealed that there are several topographic features not readily apparent from the contours in Figure 3 that are worthy of note. The north wall of the canyon in the vicinity of the measuring station, from a depth of 55 to 70

fathoms, appears to have an inclination of 60 degrees. The slopes rise more gradually on the ridge immediately east of the station and on the south side of the canyon.

While it would appear from the contour chart that the canyon axes and sides are relatively straight and uniform, the full complexity of the canyon topography is not detailed by the soundings. Very likely, unknown features of the relief exert some local influences on the currents that move through the canyon.

III. CURRENT MEASUREMENT

Current Measurement System. The system devised is illustrated in Figure 5, and consisted of an anchored wire held taut vertically by a subsurface float to which the current meter was attached. A five-gallon can filled with concrete served as the anchor. The float, which was detachable, consisted of buoyant cinder blocks in a burlap bag clamped to the wire (Figure 6). This permitted adequate support for the meter and easy recovery. Ease of recovery was necessary because the Ekman meter had to be raised and read for each observation.

Field Procedure. Measurements were taken from the U. S. Naval Postgraduate School 63-foot research vessel, using the bathythermograph winch and wire to raise and lower the current meter system. The vessel was not anchored, but drifted for the duration of each individual measurement. The vessel was positioned for each drop by using two range lines that intersected approximately at right angles, each line being formed by objects in line on the beach. This method provided surprisingly accurate positioning, as an obvious bearing shift developed in walking only a few feet on the boat. Because of local irregularities of the bottom topography over the length of the vessel, the fathometer was used for positioning as well.

The procedure for placing the current meter at 130 meters depth was: (a) the weight and meter would be lowered approximately 80 meters; (b) the float clamped on the wire with the stopping messenger attached beneath it; (c) the starting messenger dropped; and (d) the whole system then lowered immediately to the bottom while the messenger was dropping. This procedure of dropping the starting messenger before the current meter was on the bottom was devised in order to avoid adding an additional line that could become fouled. The lines from the float to the vessel were kept slack to permit the vessel to drift freely.

After about 10 minutes of current recording the stopping messenger would be released. This was accomplished by hauling in on an auxiliary retrieving line, thereby breaking the messenger attachment to the float clamp. Release of the messenger was indicated by a sudden easing of the strain on the messenger line. After sufficient time for the second messenger to complete its descent, the meter would be brought to the surface and the readings recorded. Another measurement could commence subsequent to repositioning.

<u>Computation of Current Speed and Direction</u>. The design of the Ekman meter is such that it yields only a single mean value of the current speed and direction over the interval of an

observation. The interval used in this study was approximately 10 minutes for each observation, and was measured by the time interval between dropping the starting and stopping messengers.

The mean current speed is recorded in the form of propeller revolutions which are read directly on a dial. The number of revolutions for the duration of the observation yields the propeller revolutions per second. This is then converted into a mean current speed for the interval by referring to a National Bureau of Standards calibration curve for the instrument. The calibration curve for the meter used is shown in Appendix II.

Current direction is recorded through the distribution of balls into any of 36 compartments, each compartment representing ten degrees of the compass rose. For every 33 revolutions for the propeller a ball is released and channeled by a magnetic guide into a directional compartment determined by the instantaneous orientation of the current vane, which is free to rotate around the wire. The result is a distribution of balls in the direction toward which the instantaneous current is flowing at the time of ball release.

The mean direction has been computed as being that resulting from the vectorial sum of the ball distribution, assigning a unit value of flow to each ball. Usually, the ball distribution for a given observation fell in a direction range

less than 90 degrees. Since each ball represents 33 propeller revolutions, water flow past the meter in the directions indicated by the balls can be obtained from the ball distribution.

Measurement Limitations, Error Sources, and Equipment Difficulties. Current measurements were subject to one major limitation in the accuracy of measuring direction. That is, direction is based on fairly infrequent sampling for all but the highest speeds. For example, one ball per minute, i.e. one sampling of direction per minute, would require a fairly high flow rate of 14 cm/sec (0.28 knot) past the meter. In general, this limitation considerably overshadows any other errors inherent in direction measurement.

There are four possible sources of error in speed. First, mean speeds of less than 2 cm/sec (0.04 knot) are probably not reliably recorded due to inertia which must be overcome to start the meter (Sverdrup, Johnson, and Fleming, 1942). A second possible source of error lay in the method of starting an observation, wherein the starting messenger fell 130 meters through the water while the stopping messenger only fell 80 meters. The time of messenger drop was considered to mark starting and stopping times so that no correction was applied for this difference in distance of fall. Consequently, the meter might have run as much as 15 seconds less than the recorded

duration to yield a maximum possible error of 2.5 per cent. Thirdly, even though the meter was always lowered immediately upon release of the starting messenger, the possibility existed that the messenger might on occasion have reached the meter before the meter reached the bottom. This is extremely unlikely; in addition, the recording of zero and near zero speeds gives reason to believe that no errors from this source actually occurred. And fourthly, horizontal oscillations of the float could have introduced velocity errors; however, since the meter is so near the anchor, the meter movement that could result from even large horizontal movement of the float would be very small. Accordingly, this error source is considered negligible.

Taking the above factors into consideration, the maximum error in the mean speed measurements is believed to be no greater than ten per cent. Mean direction measurements are least reliable for the slowest speeds, but for moderate and stronger speeds they are probably accurate to within ten degrees.

A major equipment difficulty turned out to be the strength of the wire on the bathythermograph winch. The wire (3/32 inch, 7 x 7 strand, stainless steel) broke on the final day of observations. Whereas the wire had a 1,000 pound test

strength, and the weight of the anchor, wire, and meter totaled only 100 pounds submerged, the wire was not strong enough to withstand the accelerations due to the sudden stops and starts that were inherent in the operation of a standard bathythermograph winch.

Wind, sea, and swell were occassional annoyances. Strong winds produced rapid drift of the boat which necessitated reducing some measurements to less than ten minutes. Anchoring, had it been available, might have been a solution to this problem.

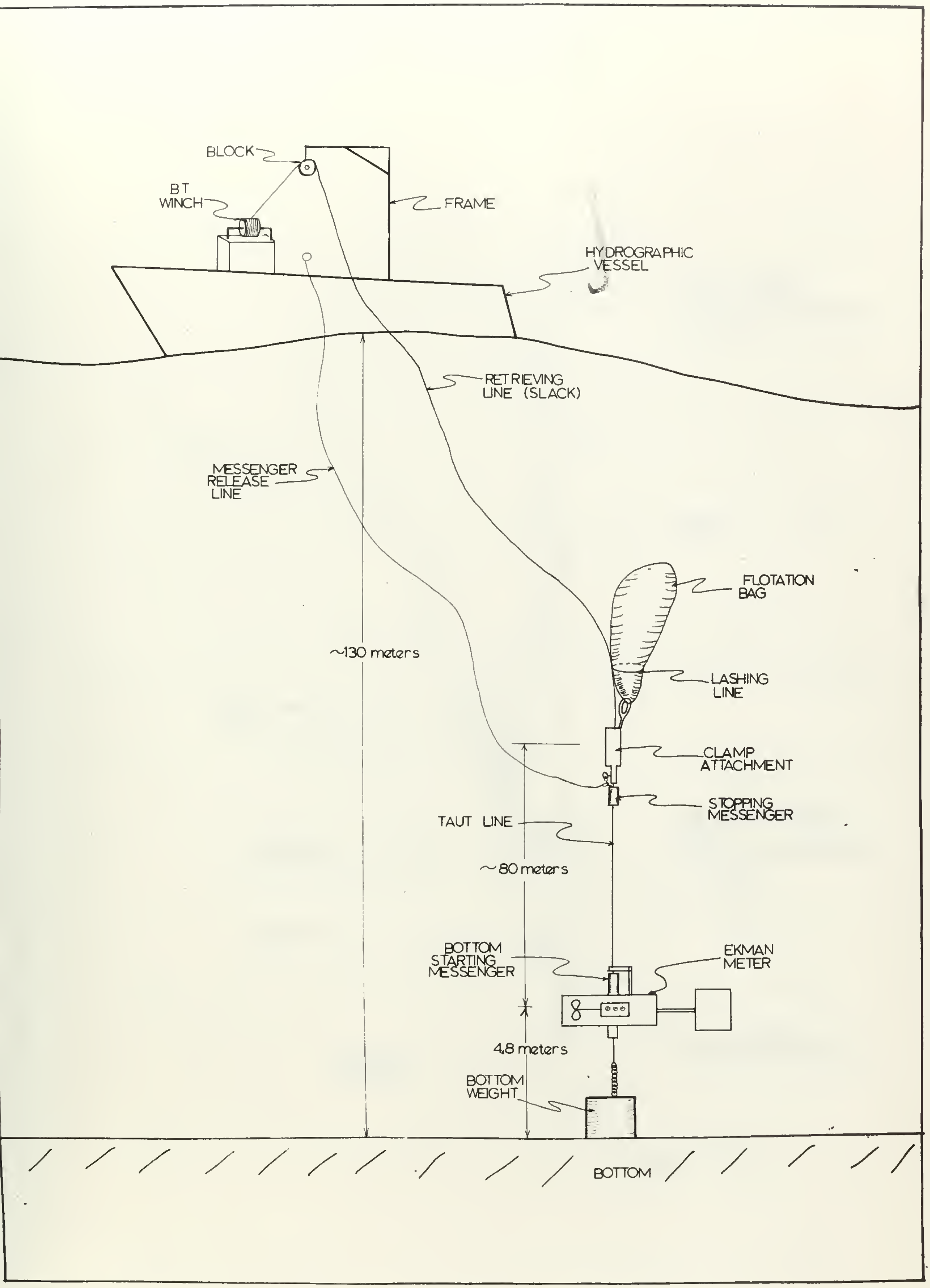

Figure 5. Current Measuring System.

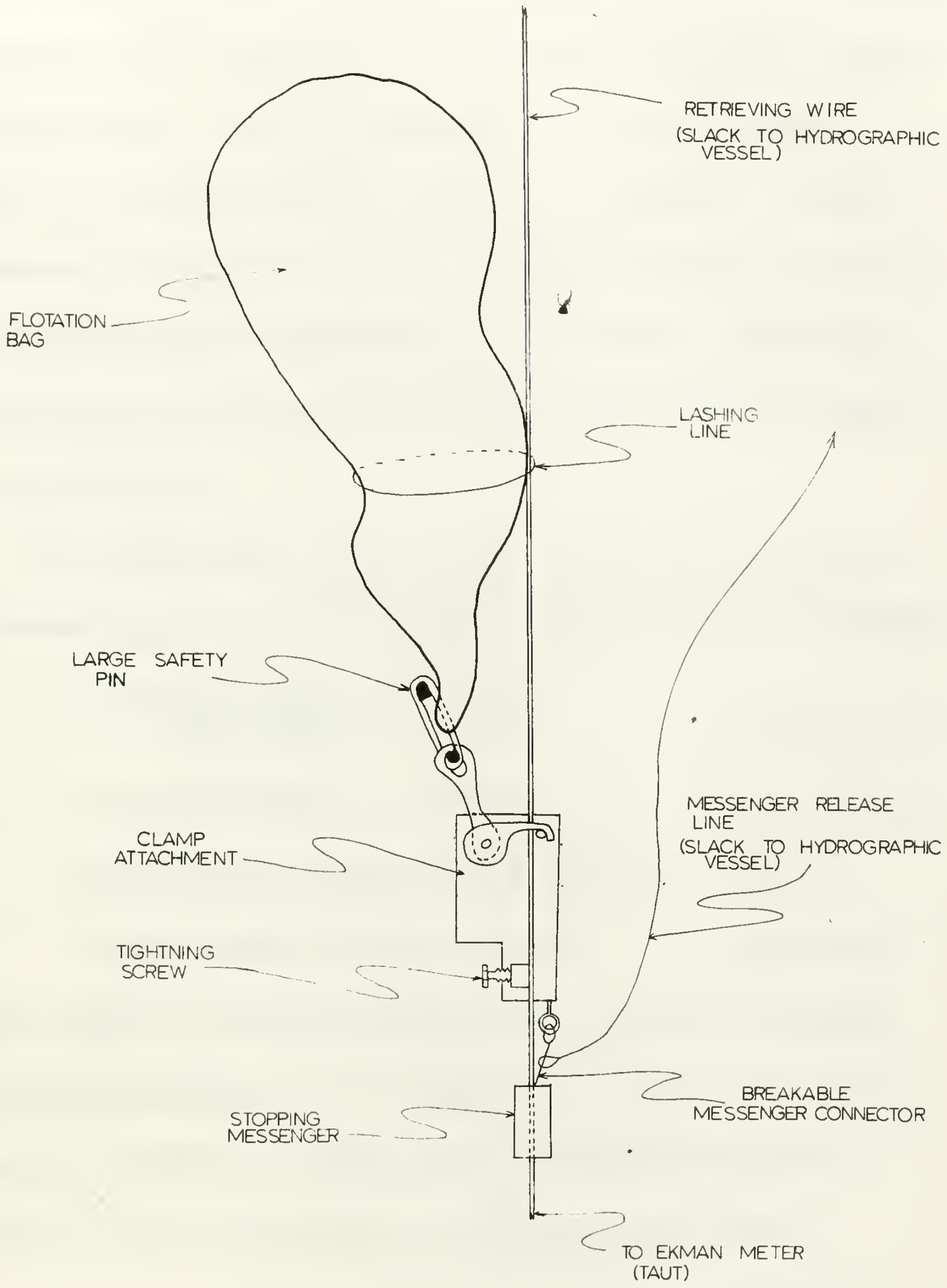

Figure 6. Flotation and Messenger Release System.

IV. OBSERVED BOTTOM CURRENTS

Basic Current Data. A total of 77 observations were made on nine different days in February and March, 1965. In all cases the meter was 4.8 meters (15.7 feet) above the bottom. Except for the first day, all measurements were made at the same location in a mean depth of 130 meters (72 fathoms). Actually, measurements were taken over a small area, outlined in Figure 3, in which the depths varied from 55 to 77 fathoms, with 88 per cent being in the range 65 to 75 fathoms and 66 per cent being 70 to 75 fathoms.

Few readings were made on the first two days. However, the remaining seven days consisted of readings taken as follows:

Average duration of individual observations	10.2 minutes
Average frequency of observations	29 minutes
Average daily number of observations	10.3
Average daily duration of survey	5.0 hours

Thus, currents were measured twice each hour on the average, for a total metering time of 20 minutes per hour. This rigorous sampling interval was adopted so as to enable satisfactory analysis of the measurements for possible tidal effects.

The currents observed during each survey are shown in Figures 10 through 14; they are plotted as vectors on the tide

curve that prevailed. The observed speed and direction measurements are summarized in Figures 7 through 9 in the form of histograms and cumulative curves. The raw current data on which the figures are based are contained in Appendix III, along with wind and swell observations made on each day. In Figures 7, 8, 9, and 15, the number of speed and direction measurements differ from 77 for various reasons: three of the readings have zero speed and consequently no direction; four have a speed but no direction due to compass malfunction; and two have some indication of a direction but no useful speed due to partial binding of the propeller.

The characteristics of the observed current speeds and directions will be discussed first, followed, in succeeding sections by the relation of the currents to the tides and to other possible causitive factors.

Observations of Speed. The 75 mean current speeds measured during all of the surveys are summarized in Figure 7. According to the figure, observed currents in the lower and moderate speeds, generally less than 23 cm/sec(0.45 knot), were most frequent. There were eight readings out of the 75 that were 25 cm/sec (0.5 knot) or greater; the highest speed was 41 cm/sec (0.8 knot), with the second highest being 32 cm/sec (0.6 knot).

The median speed of all the observations was 10 cm/sec (0.2 knot).

During the individual surveys made on each of the latest seven days, shown in Figures 11 through 14, at least one daily observation of 17 cm/sec (0.3 knot) or greater was observed; and in fact all these days, except one, had occurrences of at least 20 cm/sec (0.4 knot). Further examination shows that the speed measured over a number of hours was variable, with a tendency for the strongest currents to occur in the two or three hours on either side of low tide. However, each survey revealed a somewhat different pattern in speed, so that a high degree of predictability cannot be expected from knowledge of the tide characteristics observed on a given day.

One survey of particular interest was that of 17 February (Figure 11). The speed was nearly zero for 2 1/2 hours during and after high tide, followed by a strong current of 26 to 32 cm/sec (0.5 to 0.6 knot) flowing steadily up the canyon for at least 1 1/2 hours.

Observation of Direction. The frequency distribution of current directions, as shown in Figure 8, displayed a well-defined bimodal distribution in which the two modes are separated by approximately 180 degrees. A comparison of these directions with the orientation of the canyon axes in the

vicinity of the observation station (Figure 3) clearly indicates that these directions represent predominant up-canyon and down-canyon flow. In addition, the polarity of the flow in these two directions is related to the tide, the flow tending to move up-canyon on the falling tide and down-canyon on the rising tide. This relationship with the tide is shown in Figure 9 and will be discussed further in the next section.

The two modes evident in Figure 8 account for 68 per cent of all the observations, of which 47 per cent were up-canyon in the direction range of 000° to 040° true, and 21 per cent were down-canyon from 190° to 230° true. These differences in percentage may appear to indicate that up-canyon flow predominates at the measuring station; however, they are probably the result of there having been proportionately more observations taken when the current was flowing up-canyon than down-canyon (49 observations on the falling tide versus 21 observations on the rising tide). The evident relationship of the current direction to the tides suggests that the intervals of up and down-canyon flow are approximately equal over a multiple of tidal periods.

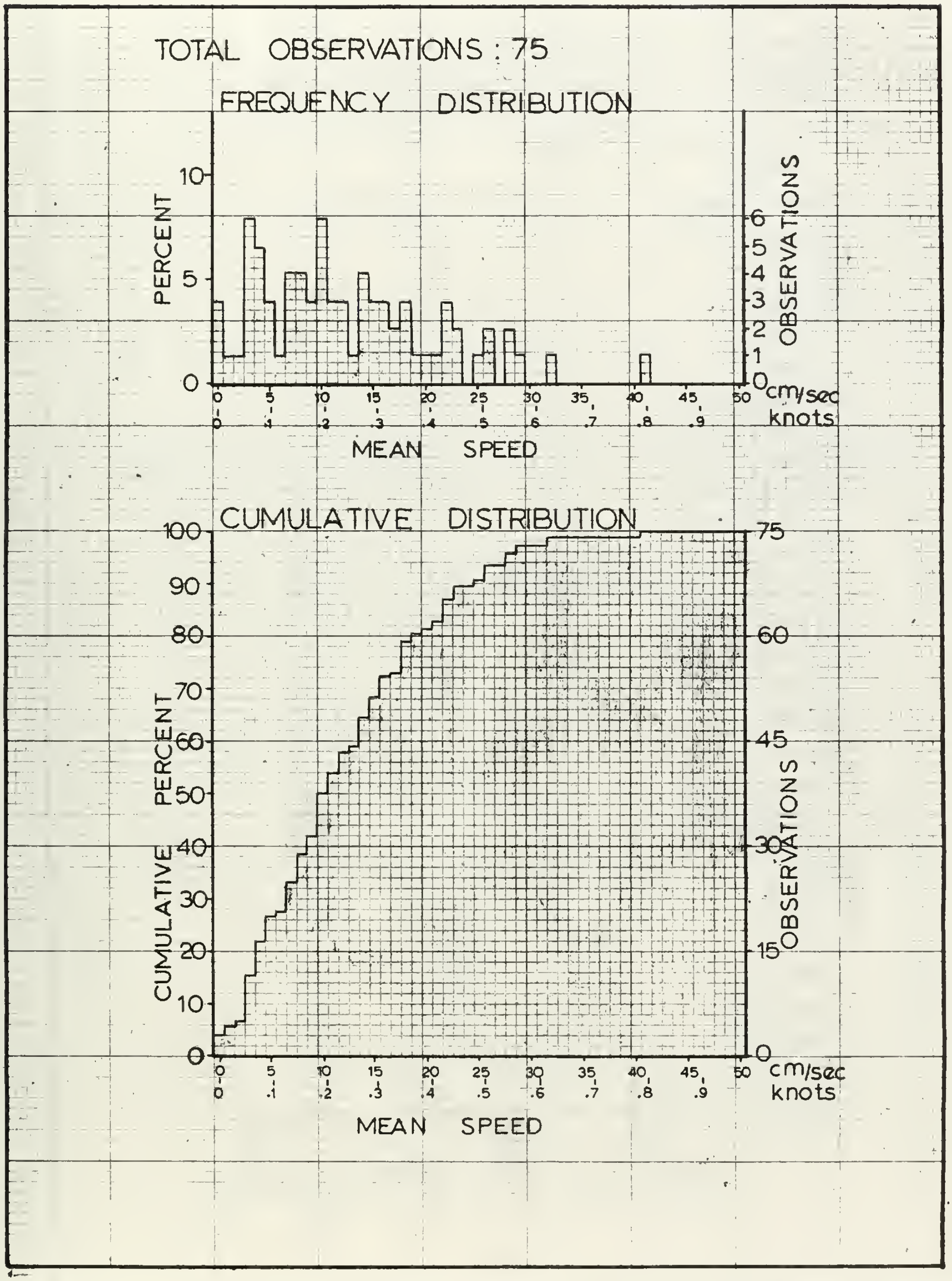

Figure 7. Statistical Distribution of Mean Current Speed.

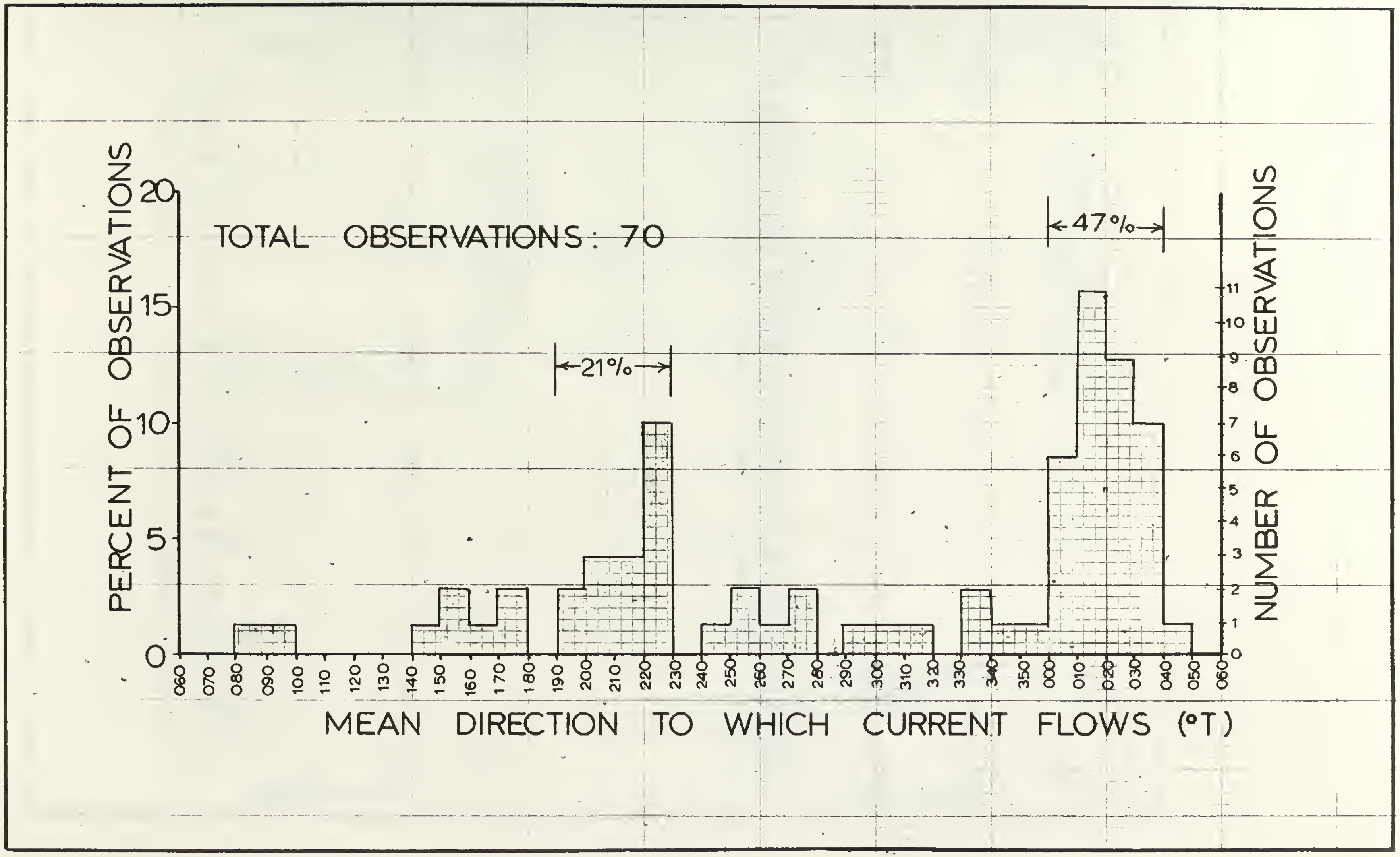

Figure 8. Frequency Distribution of Mean Current Direction.

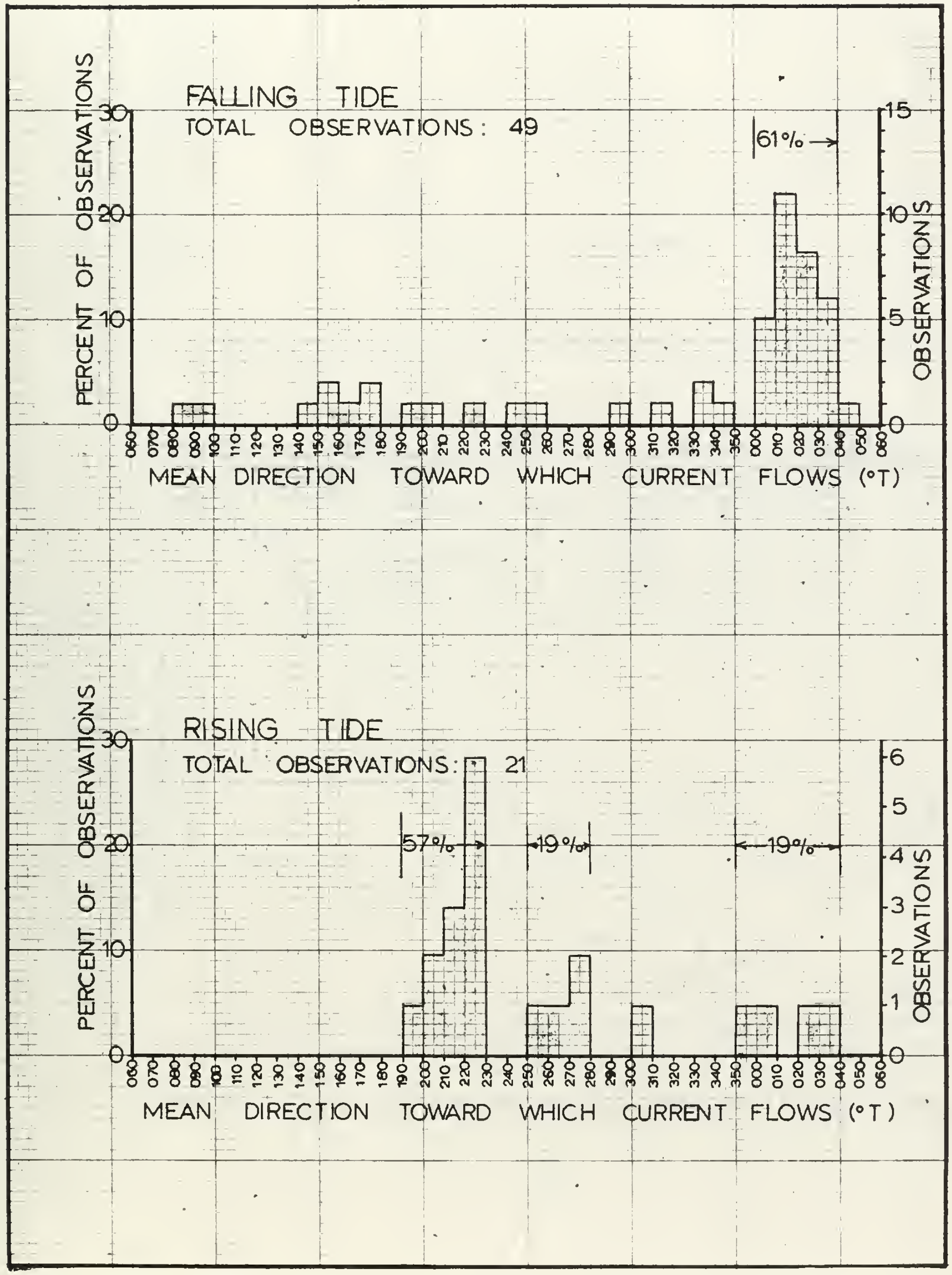

Figure 9. Frequency Distribution of Mean Current Direction for Falling and Rising Tide.

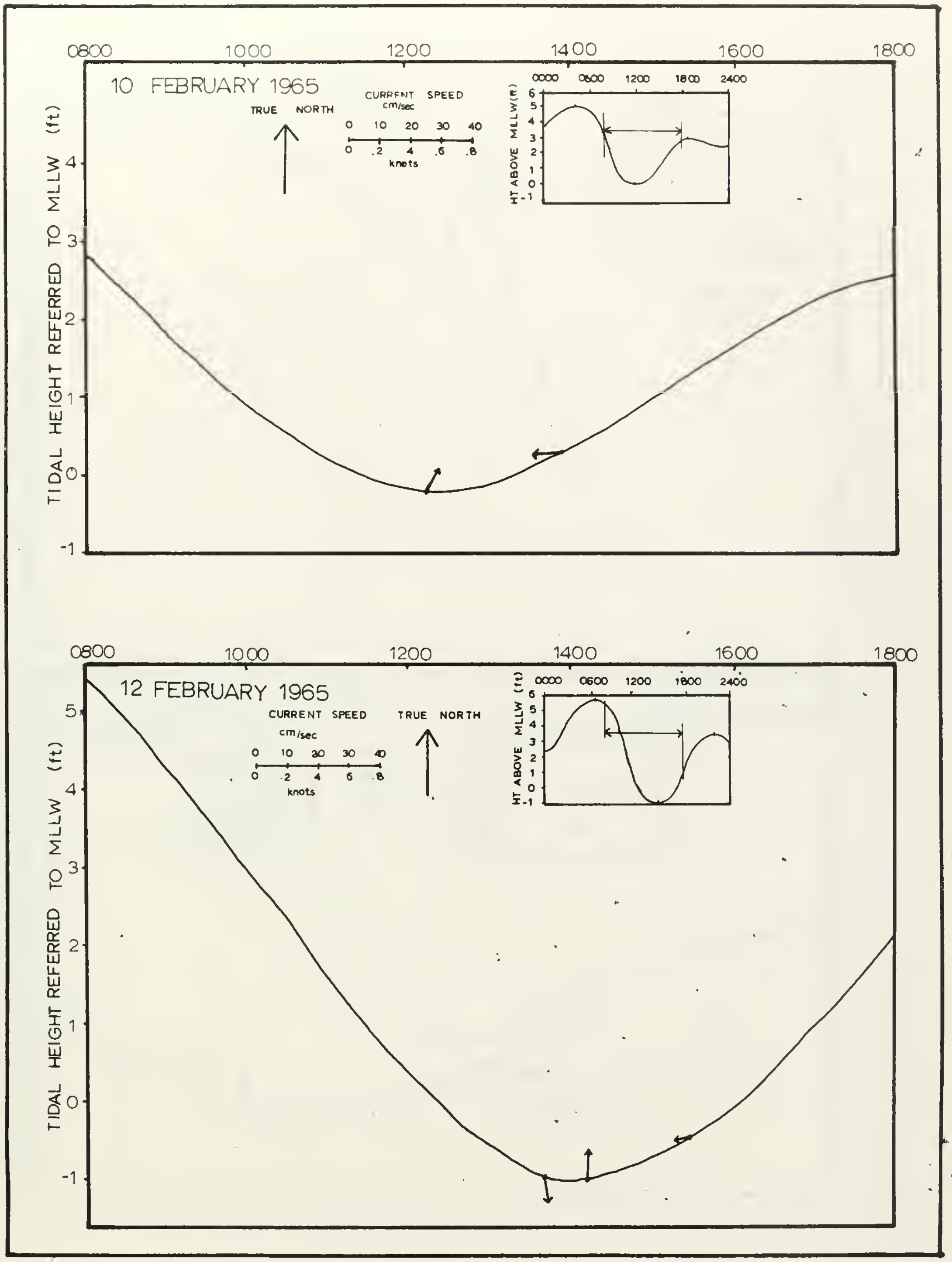

Figure 10. Current Observations and Tide for 10 and 12 February 1965.

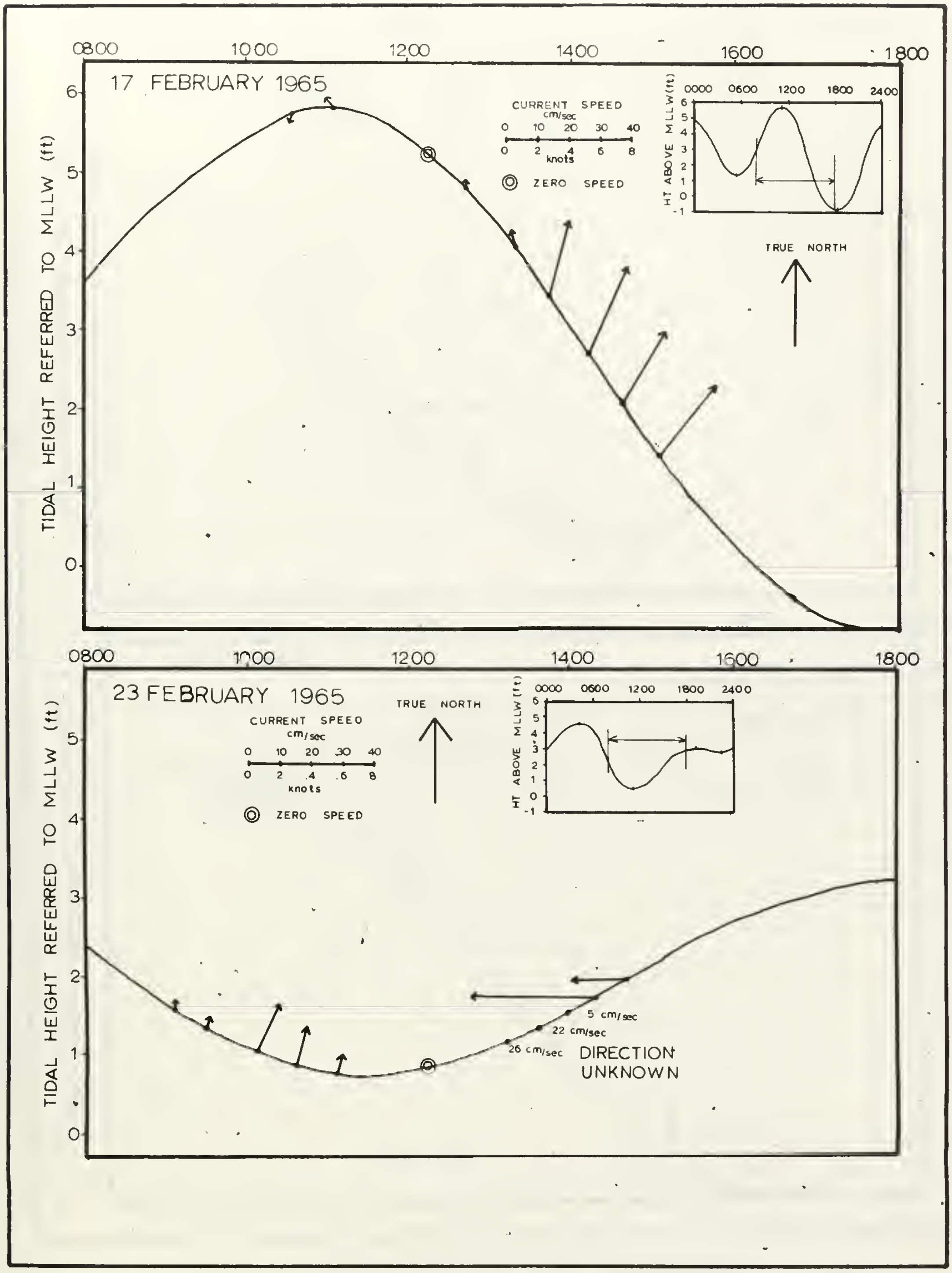

Figure 11. Current Observations and Tide for 17 and 23 February 1965.

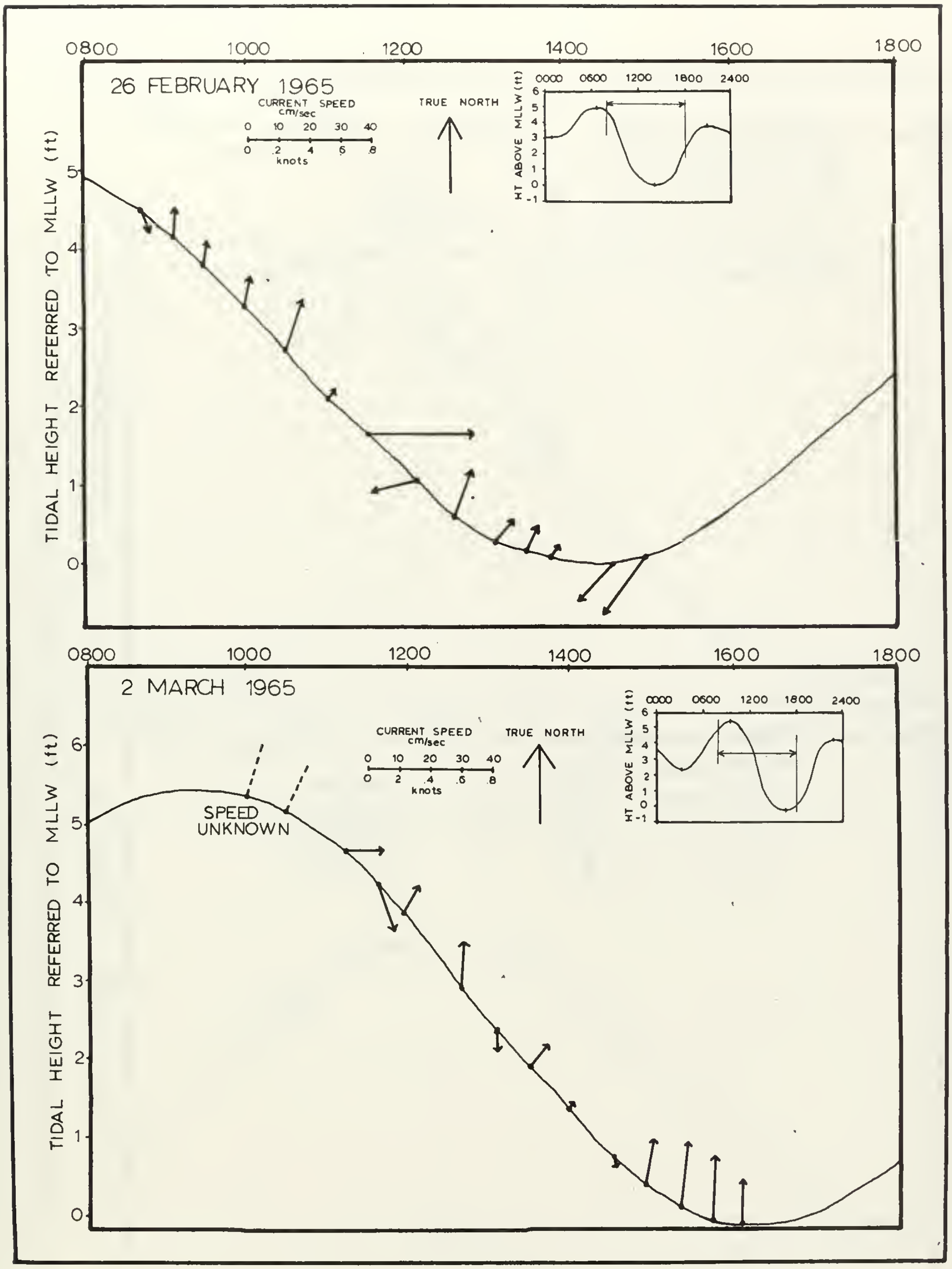

Figure 12. Current Observations and Tide for 26 February and 2 March 1965.

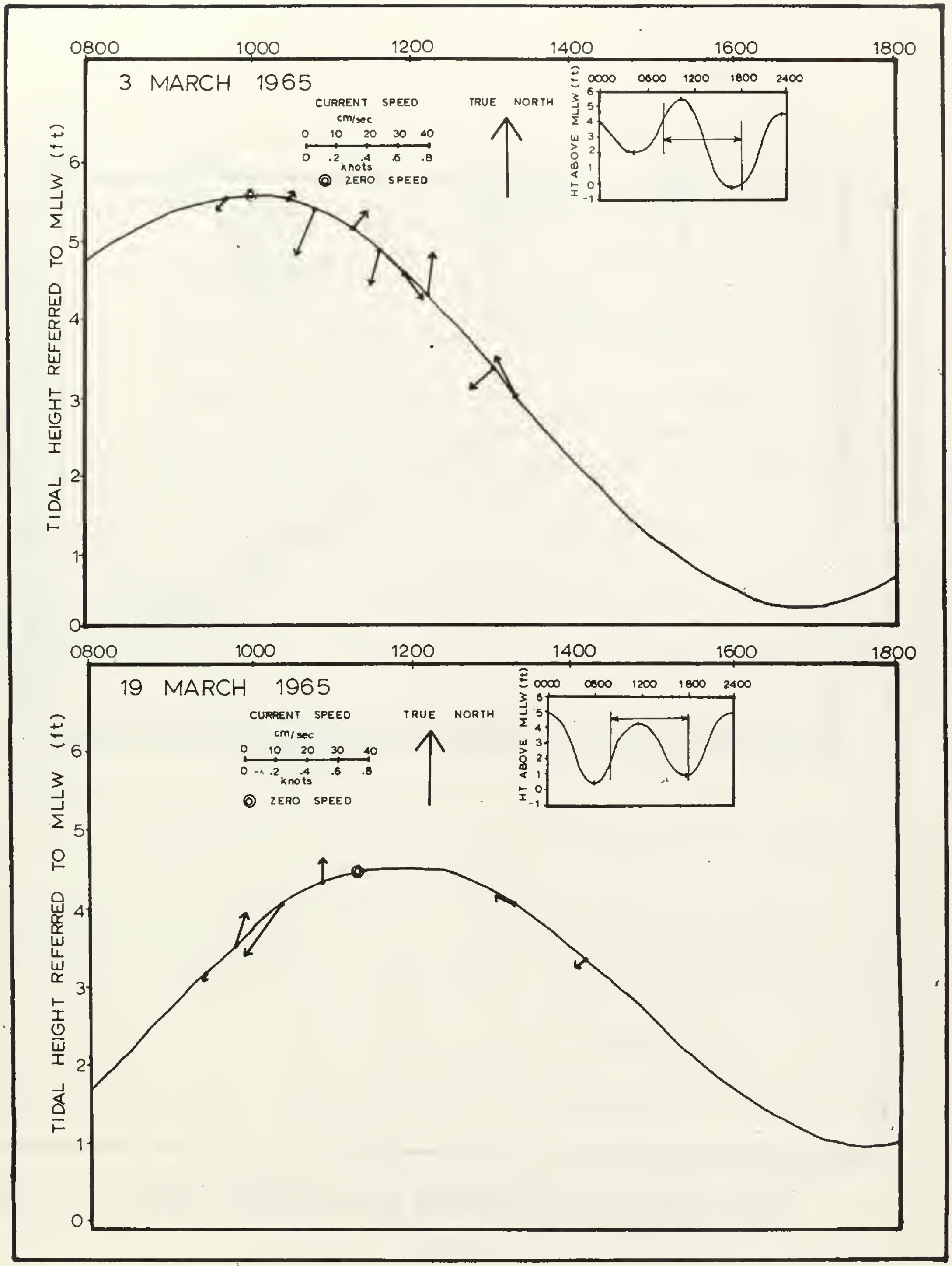

Figure 13. Current Observations and Tide for 3 and 19 March 1965.

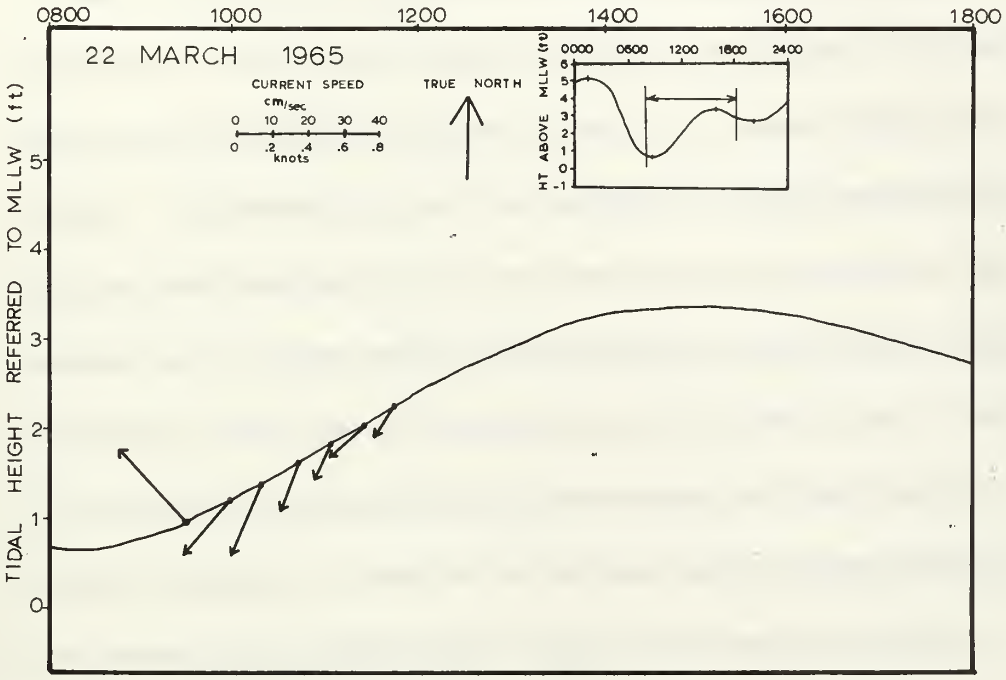

Figure 14. Current Observations and Tide for 23 March 1965.

V. CURRENTS IN RELATION TO THE TIDES

Each set of current measurements was plotted on the tide curve prevailing on the day of the observation (Figures 10 through 14) in order to examine the relationship with the tide. The tide curves shown were recorded in Monterey Harbor on a standard recording tide gage maintained by the U. S. Naval Postgraduate School. Differences in time and height of the tide between Moss Landing and Monterey Harbor are small and were neglected (the heights are the same and the times amount to about three minutes difference). The tide at Monterey is of the mixed type, in which the two high waters and the two low waters each day exhibit a diurnal inequality. Most of the current surveys were made over the interval from higher high through lower low to lower high water.

As previously discussed, Figures 10 through 14 reveal a general correspondence between the direction and strength of flow and the tide stage. All of these surveys have been combined to produce a composite picture of the current velocity in relation to the tidal stage, and this is shown in Figure 15. The figure displays integrated vectors of the current velocities from all surveys on an artificial tide curve of sinusoidal profile. The period of this tide is 14 hours, which is the nearest hour to the average of the semidiurnal tidal periods over which the surveys

were made. The figure was constructed by vectorially averaging all of the individual current velocities occurring over a time interval of 38 minutes before to 38 minutes after the tidal hour (measured from the time of high and low tide). This produced a small overlap between hours but a larger overlap midway between high and low tide because the time interval between high and low water is sometimes less than seven hours. All current vectors within a given time interval were averaged irrespective of the tide range on each day.

The integrated hourly current vectors shown in Figure 15, as well as the histograms shown in Figure 9, reveal a well-defined up-canyon flow on the falling tide and down-canyon flow on the rising tide. The two figures show that the up-canyon flow is mostly in the direction of the north branch, while the down-canyon flow appears to be in the direction of both branches although favoring the north branch.

Figure 15 also shows that strong currents are associated with hours around low tide and weak currents with high tide.[1] An assymmetry of the current variation with respect to the tide is also revealed by the difference in magnitude of the two velocity vectors shown in the figure for the falling tide and the rising

[1]The surface rotary tidal currents at San Francisco lightship show this same tendency (Wiegel, 1964).

tide. This difference amounts to 2.5 cm/sec (0.05 knot), and may represent a steady down-current flow of 1.25 cm/sec (0.025 knot) on which tidal currents are superimposed. Other interpretations are possible for this difference in flow, however, and these include: (a) the flow in the two branches of the canyon differing in the down-canyon and up-canyon directions; (b) changing environmental and tidal conditions from one day of sampling to another; and (c) unrepresentitiveness of the small sample of measurements made on the rising tide. In any event, it appears there may be slow net flow in a down-canyon direction. This could represent seaward return flow of shoreward wave transport or, if existant, the flow of heavier density water derived from evaporation in Elkhorn Slough that extends into the coastal plain from the canyon head.

Another interesting observation is that, contrary to expectation, the bottom currents flow offshore with the rising tide and onshore with the falling tide. It seems likely that the bottom currents represent a counterflow moving in opposition to the onshore-offshore tidal flow that is presumed to occur in the surface water over the continental shelf of the bay. Recent observations of differential movement of water with depth around the Hawaiian Islands showed that offshore and onshore tidal components at the surface were compensated by opposite currents

along the bottom (Laevastu, et al., 1964).

An indication of the relationship between current speed and tide range is shown in Figure 16, in which the three highest speeds for each survey are plotted against the appropriate tidal range (in one instance only two observations were made on the rising tide). The values plotted are those near low tide since the highest speeds observed tended to occur near low tide. Because tidal currents are normally stronger when the range of tide is greater, one would expect to see this same relationship hold for the bottom currents. The figure shows that it did hold for falling tide but not for rising tide. The suggestion from the figure is that on the rising tide, current speed varied inversely with range, but this very likely resulted from insufficient sampling of the current speed during rising tide. The strong bottom currents observed on the rising tide probably are not the result of reduced tidal stage.

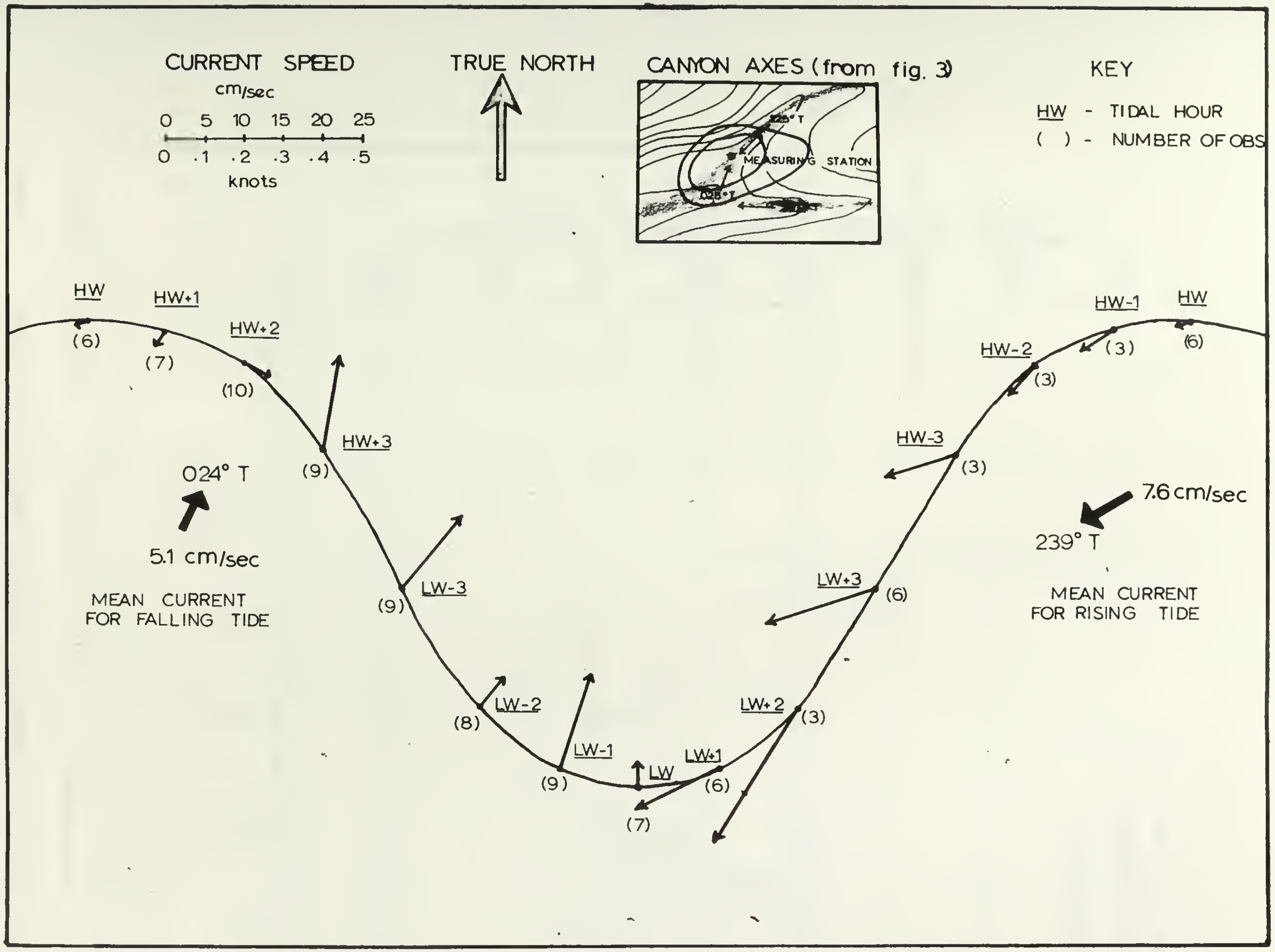

Figure 15. Average Current Velocity in Relation to a Sinusoidal Tide Curve. Each hourly vector is an average of the observations 38 minutes on either side of the vector.

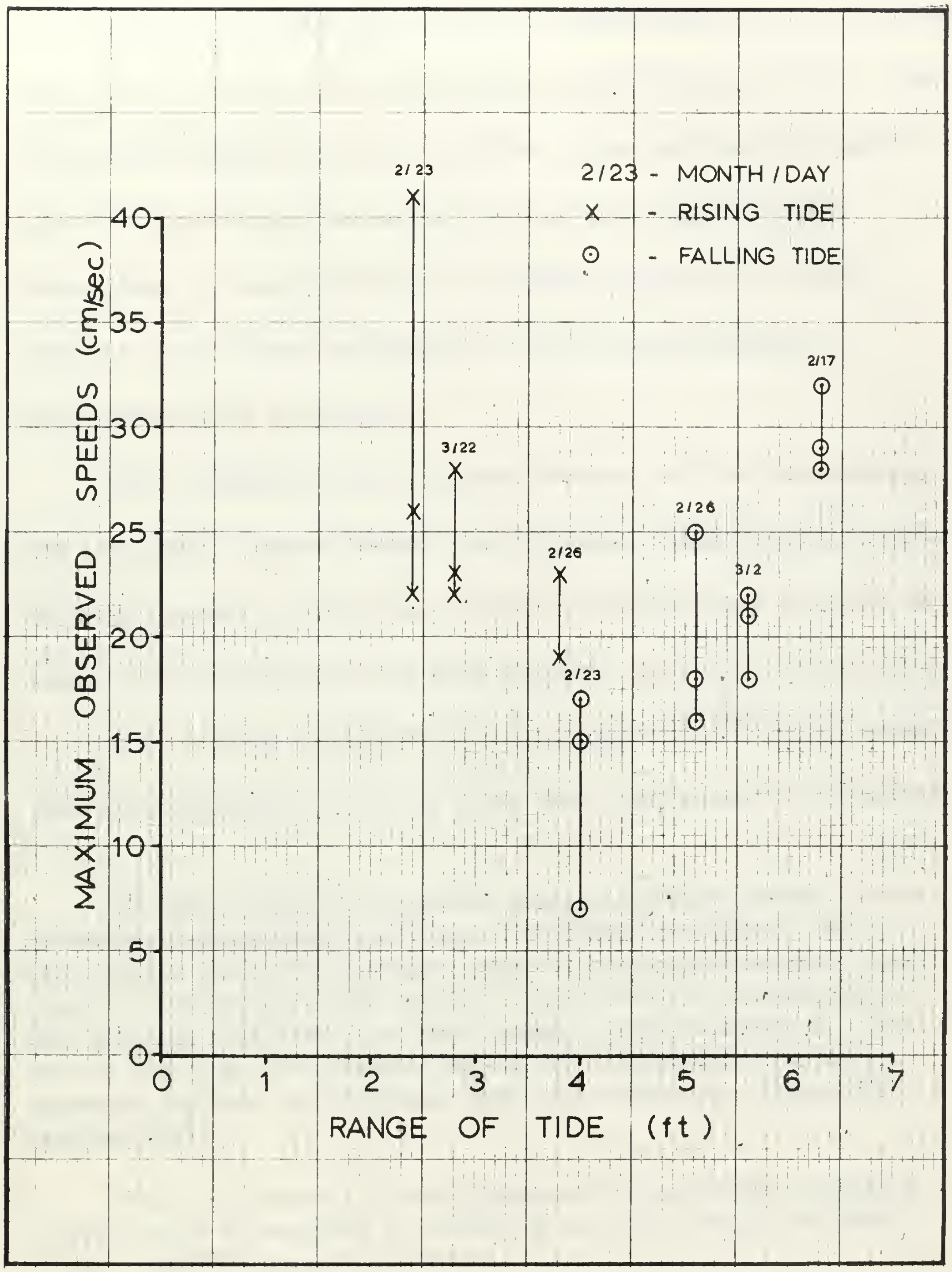

Figure 16. Maximum Current Speeds Observed for Various Ranges of Tide. The three highest speeds were used from each survey.

VI. OTHER POSSIBLE FACTORS INFLUENCING BOTTOM CURRENTS

Canyon topography and tides have been discussed in connection with their influence and relationship to the bottom currents. These two factors clearly dominate; however, other factors may have an effect whenever they are present. The latter fall into two categories; (a) oscillations in long-period waves which "feel bottom" in the depths considered, and (b) mass-transport phenomena other than tidal.

Swell, seismic waves, internal waves, and bay oscillations are long-period waves capable of influence to considerable depths. Seismic waves did not occur. Swell can be ruled out because the longest period recorded was nine seconds, and this was too short to permit "feeling bottom" at the measuring depth. Internal waves[1] and bay oscillations[2], on the other hand, are known to be common

[1] La Fond (1962) has reported measuring near-bottom internal waves producing flow sufficient to transport sediment. He pointed out that if the internal wave is moving shoreward, water particle motions near the bottom in the mean will be greater in the offshore direction, and net transport will be offshore. Due to the fact that the trough is nearer the bottom than the crest, stronger currents are offshore under the trough in a shoreward moving wave.

[2] The U. S. Army Corps of Engineers is presently funding a model study of seiching in Monterey Bay, the results of which should be available late in 1965.

in coastal regions and to have periods that can be recorded by the use of the Ekman meter. For the current observation frequency of 30 minutes that was used in the study, harmonic disturbances with periods less than about an hour cannot be delineated. Several of the surveys, particularly those of 2, 3, and 19 March (Figures 12 and 13) appear to reveal relatively short-period oscillations and fluctuations imposed on the prevailing current. Reversing currents having a period of half an hour to an hour were earlier observed in the canyon head by a diver (Shepard, 1947; Appendix I). It is also of interest here to note that the tide record for Monterey Harbor often exhibits 20 to 40 minute oscillations of about four to ten centimeters amplitude.

Onshore mass transport by wind waves, swell, and surf beat might produce a down-canyon compensating flow, such as the measured 1.25 cm/sec (0.025 knot) net down-canyon flow. Long-shore currents directed toward the canyon head could also be responsible. Additionally, quasi-permanent bay currents could have a similar effect; however, no significant currents of this nature are known to exist in Monterey Bay.

VII. CONCLUSIONS, RECOMMENDATIONS, AND ACKNOWLEDGMENTS

Conclusions. Measured current flow was found to be influenced by the canyon topography. The current follows the canyon axes and flows seaward (down-canyon) on the rising tide and coastward (up-canyon) on the falling tide. Current reversals approximately coincide with the times of high and low tide and show a predominate tidal periodicity. The association of down-canyon flow with a rising tide is contrary to expected direction of water motion, since flooding into the bay is required to raise the water level. It thus appears that the current in the canyon bottom is a compensatory current or countercurrent tending to return water seaward. The situation with falling tide is the converse.

Maximum current on every tide cycle was at least 16 cm/sec (0.3 knot) and usually 21 cm/sec (0.4 knot). Hjulstrom (1939) reported that medium sand erosion starts in currents with a mean velocity of 20 cm/sec (0.4 knot), measured one meter above the bottom. Both finer and coarser sediments require higher velocities for erosion. Transportational velocities are much lower than erosional velocities.

Turbidity currents are generally accepted as the major cause of canyon erosion. If currents of similar strength, as observed in the canyon, exist on the surrounding shelves and slopes, there may be considerable transport of sediment into the canyon from a

large area, thus providing a sediment source for turbidity currents. Observations of such shelf currents have recently been reported (Shepard, et al., 1964; and Deepstar Log #1).

The maximum observed current was 41 cm/sec (0.8 knot), with the six hours centered around low tide generally having considerably stronger currents than the similar period centered around high tide. Range of the tide appears to have a direct influence on the maximum speed observed during falling tides. The inverse relationship observed between the tide range and current speeds during rising tides seems related to the local topographic convergence of the down-canyon flow.

A net down-canyon flow of 1.25 cm/sec (0.025 knot) appears to exist. It very likely results from shoreward transport of water by wind waves, swell, and internal waves, and represents a compensating flow.

Recommendations. Subsequent current studies of this nature can be improved by: a) using a continuous recording current meter for detection of small-scale current influences and for time continuity; and b) measuring currents at various levels, supported by measurements of the thermal structure throughout the water column, for a more complete understanding of the current regime and its causes in canyons.

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Appendix I

RESUMES OF PAPERS PUBLISHED ON BOTTOM CURRENT OBSERVATIONS IN SUBMARINE CANYONS

The following resumes are presented in reverse chronological order. The Westinghouse Defense and Space Center (1964-65) is the source of all the references in the first two resumes.

Investigator. R. Presbitero (Deepstar Log #13)

R. F. Dill (Deepstar Logs #11 and 13)

J. Houchen (Deepstar Log #12)

D. L. Inman (Deepstar Log #12)

F. P. Shepard (Deepstar Log #11)

Location. San Lucas Canyon, Baja California

Date. January and February 1965

Method. Diving Saucer

Observation. On five different days, near-bottom currents within the canyon from shallow depths to nearly 300 meters varied in speed from zero to 0.4 knots (21 cm/sec). Down-canyon currents predominated and were strongest below 170 meters. Ripple marks and rock scour were observed at various depths greater than 170 meters. There was very little evidence of current activity at shallower depths.

Investigator. E. L. Winterer (Deepstar Log #1)

D. L. Inman (Deepstar Log #1 and 8)

F. P. Shepard (Deepstar Logs #1 and 8)

R. F. Dill (Deepstar Log #2)

E. A. Murray (Deepstar Log #7)

Location. Scripps and La Jolla Canyons, California

Date. November and December 1964

Method. Diving Saucer

Observation. Maximum current in Scripps Canyon was 0.5 knot (26 cm/sec) at the depth of 142 meters. The current was down-canyon. Also noted were distinct signs of current erosion and an observation of the bottom being set in motion by the current (Deepstar Log #1).

Maximum current in La Jolla Canyon was 0.45 knot (28 cm/sec) at a depth of nearly 160 meters. The current pulsated from zero to 0.45 knot in a down-canyon direction. Sediment was observed being transported with a current of about 0.4 knot (21 cm/sec). On the same dive, currents were absent at depths shallower than 150 meters (Deepstar Log #2).

Subsequent dives yielded a current of 0.1 to 0.2 knot (5 to 10 cm/sec) at 50 meters depth in Scripps Canyon (Deepstar Log #7) and slight currents in both canyons at depths to 200 meters (Deepstar Log #8).

Investigator. F. P. Shepard, J. R. Curray, D. L. Inman, E. A. Murray, E. L. Winterer, and R. F. Dill (1964)

Location. Scripps Canyon, California

Date. February 1964

Method. Diving Saucer

Observation. Down-canyon currents as great as 0.2 knot (10 cm/sec) were reported at many places in the canyon, but especially at depths greater than 100 meters. There were similar down-slope velocities on the open shelf and slope near the canyon at depths greater than 60 meters. To-and-fro swell motion existed at shallow depths. Internal waves, surf beat, or seaward return flow of water carried inshore by surface swell were suggested as possible explanations for the currents.

Investigator. F. P. Shepard (1947)

Location. Monterey Canyon, California

Date. 30 October through 6 November 1947

Method. Diver

Observation. The diver reported weak currents moving up and down the canyon in shallow waters of the canyon head. Poor visibility hindered more complete observations.

Investigator. F. P. Shepard (1948)

Location. Scripps and La Jolla Canyons, California

Date. 1947 and 1948

Method. Diver

Observation. At depths less than 57 meters (31 fathoms) the diver estimated feeble currents generally flowing up or down-canyon and reversing direction during a period of half an hour to an hour. There was on observation of a non-reversing current as great as 0.5 knot (26 cm/sec).

Investigator. F. P. Shepard, R. Revelle, and R. S. Dietz (1939)

F. P. Shepard and K. O. Emery (1941)

F. P. Shepard (1948)

Location. California coastal canyons, shelves, slopes, troughs and ridges, including Monterey Canyon

Date. 1938 and 1939

Method. Ekman meter

Observation. Several hundred measurements (perhaps 300) were made in numerous locations. The meters were generally 125 to 200 centimeters above bottom. Maximum current speeds of 0.4 to 0.5 knot (21 to 26 cm/sec) were found in various canyons at depths from about 90 to 840 meters. Directions of movement tended to follow canyon axes. Reversals in direction occurred at

relatively short but irregular intervals of time.

Sixteen observations in Monterey Canyon yielded a maximum speed of 26.9 cm/sec (0.5 knot) with no reported direction. The instrument was 2 meters above the bottom in a water depth of 91 meters (50 fathoms).

Harmonic analysis of measurements in three of the Southern California canyons indicated to the investigators that the tide was not a factor of any importance in causing the currents. The total flow up-canyon appeared to be of the same order as flow down-canyon. Considering all observations, the currents were suggested as being related to "internal waves or irregularly moving eddies with vertical axes".

Investigator. H. C. Stetson (1937)

Location. Georges Bank Canyons, Atlantic Ocean

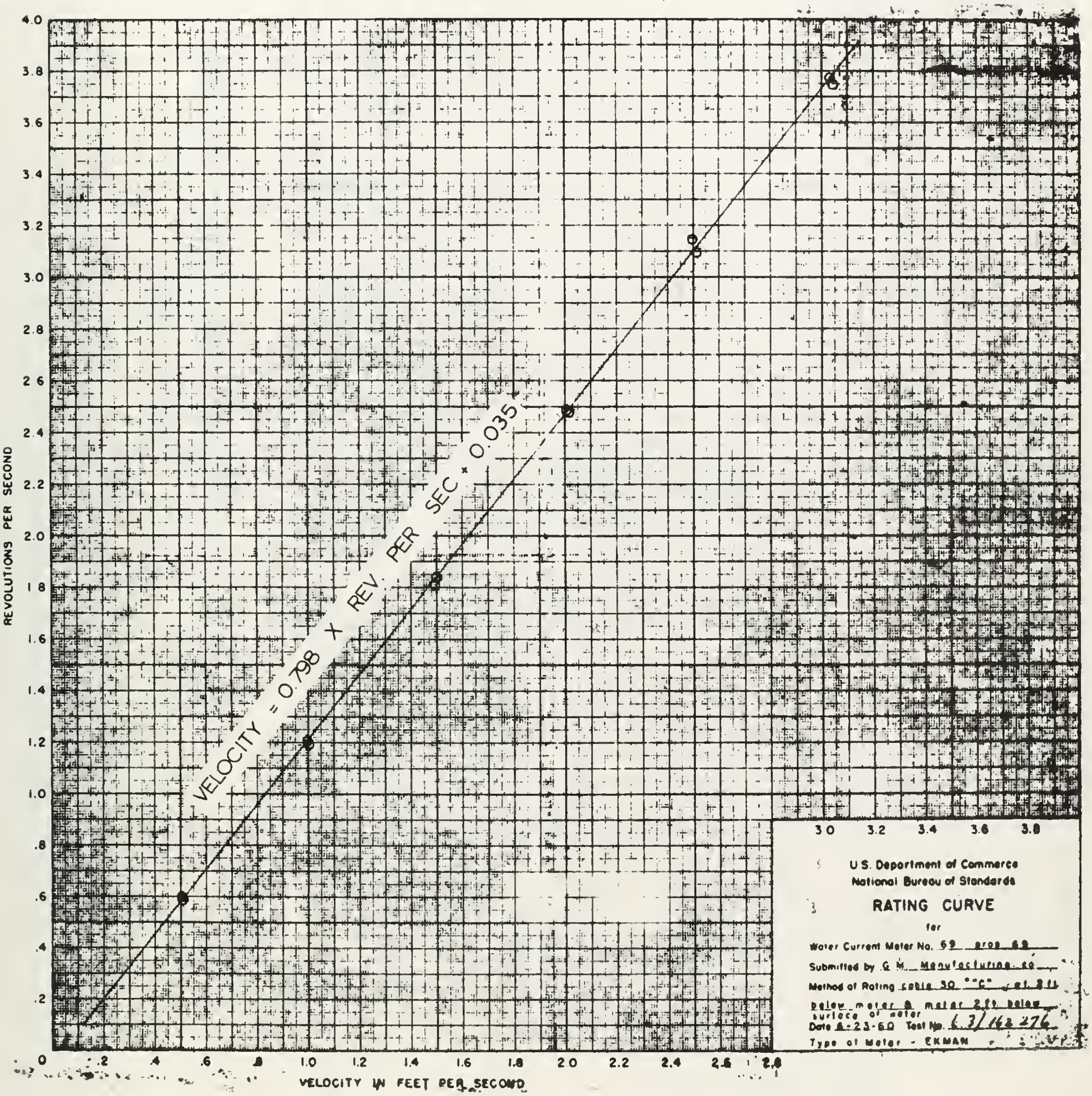
Date. 22 to 26 July 1936

Method. Ekman meter

Observation. Single measurements 25 to 28 centimeters above the bottom in water depths of about 150 meters (46 fathoms) on the shelf and 480 meters (146 fathoms) in the canyons showed maximum speeds of 11 to 12 cm/sec (0.2 knot) for both locations. The movements were interpreted as tidal in nature.

Appendix II

CALIBRATION CURVE FOR THE EKMAN CURRENT METER



Appendix III

CURRENT, TIDE, WIND AND WAVE DATA

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{O}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{O}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
10 FEB 65									
1222	N. Fork 44.5	10-00	150	*027-1 037-1	7	032	LL+0+17	S-6	W-4-6
1357	N. Fork 44	13-00	305	237-1 247-2 257-2 277-2 297-1 347-1	10	267	LL+1+52		
12 FEB 65									
1341	S. Side 65	8-11	155	017-1 127-1 167-1 217-1	9	171	LL-0+30	W-10	W-2-6
1413	S. Side 63	7-40	180	*287-1 077-1	10	002	LL+0+17	WNW-15	
1522	S. Center 70	10-00	30	257-1	3	257	LL+1+16	W-8	

*Too few balls for speed.

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{O}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{O}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
17 FEB 65									
1037	N. Center 70	15-30	120	177-1 187-1 227-1	4	197	HH-0+23	Calm	W-2-7 1/2
1106	N. Center 72	20-00	156	187-1 287-1 297-1 307-1 357-1 007-1	4	311	HH+0+06	E-8	
1217	Center 73	10-00	10		0		HH+1+17		
1248	Center 73	9-00	45	347-1	3	347	HH+1+48		
1322	Center 75	13-00	162	177-1 277-1 357-2 027-1	6	339	HH+2+22	N-9	
1348	Center 74	10-00	628	*337-1 007-1 017-1 027-5 037-1	26	014	HH+2+48		

*Too few balls for speed.

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (°T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (°T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
1414	S. Side 67	10-00	770	*357-1 027-6	32	023	HH+3+14		
1440	Center 73	12-00	808	*017-1 027-2 037-3	28	030	HH+3+40 LL-3+11	WNW-10	
1506	S. Side 68	13-00	883	*027-7 047-1 117-1	29	037	LL-2+45		
23 FEB 65									
0905	Center 77	9-00	40	007-1	3	007	LL-2+15	E-5	W-4-4
0930	N. Side 55	10-30	65	017-2	4	017	LL-1+50		
1006	Center 75	15-00	595	027-18	17	027	LL-1+14		
1035	Center 73	10-15	342	357-1 007-1 017-8	15	014	LL-0+45	Calm	
1105	Center 73	14-00	205	287-1 357-1 027-1 047-3	7	021	LL-0+15	W-6	
1215	S. Center 65	10-00	10		1	None	LL+0+55		

*Too few balls for speed.

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{o}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{o}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
1311	Center 72	7-40	510	# 15	26		LL+1+51	W-8	
1334	S. Side 67	7-10	370	# 11	22		LL+2+14	W-12	
1400	S. Side 66	7-50	75	# 2	5		LL+2+40 H-3+58		
1422	Center 73	6-15	670	207-1 247-5 257-4 267-1 277-4 287-1 297-2 007-1 017-1	41	270	LL+3+02 H-3+40		
1445	Center 74	6-40	290	237-1 257-1 267-1 287-2 297-1 307-1	18	277	LL+3+25 H-3+17	W-15	

#Magnet off pivot.

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{o}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{o}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
26 FEB 65									
0840	N. Side 68	9-00	126	127-1 147-1 167-1 177-1	7	155	HH+2+02	ESE-10	WSW-3-9
0904	S. Side 73	7-50	185	317-1 327-1 027-1 037-3	10	012	HH+2+26		
0932	Center 75	8-05	130	007-1 017-2	8	014	HH+2+54	E-6	
0959	N. Side 71	13-55	300	227-1 237-1 017-1 027-6	10	016	HH+3+21	Calm	
1026	S. Side 66	10-10	430	357-1 007-2 017-3 027-7	18	019	HH+3+48 LL-3+38		
1100	N. Side 68	18-50	152	027-1 037-3 047-1	4	037	LL-3+04		

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{O}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{O}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
1132	S. Side	14-55	880	*027-4	25	093	LL-2+32	W-3	
	60			037-1					
				047-1					
				107-1					
				117-1					
				137-2					
				167-1					
				227-2					
				267-1					
1207	Center	15-00	520	177-1	15	256	LL-1+57		
	74			217-1					
				227-3					
				247-3					
				257-1					
				277-2					
				357-1					
				007-2					
				017-1					
1238	Center	16-05	610	357-3	16	019	LL-1+26	WSW-8	
	74			007-1					
				017-5					
				027-7					
				037-2					
1304	S. Center	8-10	165	027-3	9	041	LL-1+00	WSW-11	
	72			037-1					
				167-1					

*Too few balls for speed.

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{O}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{O}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
1327	N. Side 71	7-20	154	017-2 027-4	10	024	LL-0+37		
1348	N. Side 58	7-45	80	027-2 037-1	5	030	LL-0+16	WSW-8	
1436	S. Side 68	7-45	345	217-4 227-6	19	223	LL+0+32		
1458	S. Center 71	9-30	508	207-1 217-10 227-5	23	217	LL+0+54		
2 MAR 65									
1000	S. Side 62	9-55	75	357-1 017-1 037-1	#	017	HH+0+36	ENE-8	W-2-6
1027	N. Center 70	14-15	30	027-1	#	027	HH+1+03		
1111	N. Side 70	10-50	322	037-1 047-1 057-1 067-1 087-1 117-2 157-1	13	088	HH+1+47		

#Propeller not freely rotating.

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{O}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{O}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
1135	Center 74	10-30	432	157-10 167-1 177-1	18	159	HH+2+16	E-6	
1157	N. Center 71	10-05	240	027-6	11	027	HH+2+33	Calm	
1241	Center 75	10-10	326	287-1 327-1 357-1 017-6	14	006	HH+3+17		
1305	Center 74	13-15	220	167-4 177-3	8	171	HH+3+41 LL-3+18	W-5	
1333	S. Center 73	14-55	330	027-1 037-8	10	037	LL-2+50		
1359	Center 74	11-56	60	017-1 027-1	3	022	LL-2+24		
1433	S. Side 68	10-45	60	137-1 187-1	3	162	LL-1+50	W-8	
1457	S. Center 74	7-55	260	237-1 007-2 017-2 027-2	14	010	LL-1+26	W-10	
1520	N. Side 68	10-07	520	347-1 357-4 007-11 057-1	22	006	LL-1+03		

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (°T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (°T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
1545	Center 71	9-33	455	357-6 007-6 017-2	21	004	LL-0+38		
1605	Center 73	10-25	360	357-6 007-4 017-1	15	002	LL-0+17		
3 MAR 65									
0941	Center 75	10-00	95	207-1 217-1 247-1	5	244	HH-0+21	SE-7	W-1-6
1000	S. Side 73	10-05	0	None	0		HH-0+02		
1027	S. Side 74	10-10	50	017-1 037-1	3	027	HH+0+25		
1049	Center 75	10-00	390	197-6 207-4 227-1	17	203	HH+0+47		
1111	Center 76	10-00	160	007-1 027-1 037-1 047-1 167-1	8	041	HH+1+09		

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{o}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{o}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
1134	Center 75	6-05	165	177-2 197-2 227-1	12	195	HH+1+32	NW-10	
1150	S. Center 75	10-00	265	107-1 127-1 137-3 157-1 177-1 197-1	12	142	HH+1+48		
1212	Center 75	10-05	315	267-1 007-2 017-5 157-1	14	011	HH+2+10		
1302	N. Center 75	5-05	125	107-1 227-1 317-1	11	242	HH+3+00		
1319	Center 73	4-00	145	287-1 307-1 007-1 017-2	16	335	HH+3+17 LL-3+33		
19 MAR 65 0924	N. Side 69	11-25	40	227-1	2	227	LL+3+35 H-2+29	Calm	W-4-6

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{O}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{O}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
0950	Center 76	9-58	205	017-1 027-5	9	025	H-2+03		
1020	S. Side 66	9-58	460	187-1 197-2 207-3 217-3 227-1 237-4	20	217	H-1+33	W-6	
1055	Center 74	10-11	170	347-2 357-2 007-2	8	357	H-0+58		
1120	Center 74	10-00	5	None	0		H-0+33	W-9	
1316	N. Center 75	6-30	100	207-2 007-1 017-1	7	299	H+1+23	NW-14	
1408	S. Center 65	5-09	30	227-1	4	227	H+2+15		
<u>22 MAR 65</u> 0926	S. Side 70	10-00	675	307-4 317-14 327-1 357-1	28	318	LL+1+06	Calm	WSW-2-5

DATE-TIME	LOCATION (fathoms)	DURATION (min-sec)	PROP REV	DIRECTION (^{o}T-balls)	MEAN SPEED (cm/sec)	MEAN DIR (^{o}T)	TIDAL HOUR (tide-hr-min)	WIND (mph)	SWELL (dir-ft-sec)
0957	S. Center	11-02	575	207-4	22	222	LL+[illegible]+37		
	72			217-6					
				227-6					
				307-1					
1018	N. Side	10-02	550	097-1	23	205	LL+1+58		
	55			197-5					
				207-7					
				217-3					
				257-1					
1041	N. Side	10-03	370	167-1	16	207	LL+2+21		
	70			197-4					
				207-3					
				217-2					
				227-1					
1103	Center	9-00	250	207-5	12	210	LL+2+43	W-5	
	70			217-2					
1123	S. Center	9-57	305	207-3	14	227	LL+3+03		
	73			217-4					
				257-2					
				267-1					
1147	S. Center	9-57	255	217-5	11	221	LL+3+27		
	73			227-1			H-3+21		
				237-1					

Thesis
G2535 Gatje 80029
Bottom current
measurements in the
head of Monterey sub-
marine canyon.